

Studies of commutation failures in hybrid LCC/MMC HVDC systems

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Abstract: A hybrid of line commutated converters (LCCs) and modular multi-level converters (MMCs) can provide the advantages of both the technologies. However, the commutation failure still exists if the LCC operates as an inverter in a hybrid LCC/MMC system. In this paper, the system behavior during a commutation failure is investigated. Both half-bridge and full-bridge MMCs are considered. Control strategies are examined through simulations conducted in PSCAD/EMTDC. Additionally, commutation failure protection strategies for multi-terminal hybrid LCC/MMC systems with AC and DC circuit breakers are studied. This paper can contribute to the protection design of future hybrid LCC/MMC systems against commutation failures.

Keywords: LCC HVDC, MMC HVDC, Modular multilevel converter, Hybrid LCC/MMC, Commutation failure, multi-terminal DC, Fault protection.

1 Introduction

Renewable energy, like wind and solar power, is widely accepted as a key solution to cope with anthropogenic global warming and climate change and achieve sustainable development [1]. However, large-scale renewable resources

and load centers usually reverse distribute over long distances. Technologies with long-distance and bulk-power transmission capabilities, such as high-voltage alternating-current (HVAC) and high-voltage direct-current (HVDC), are the main options to transmit renewable power to energy consumers. The HVDC transmission technology will be preferred when the length (so-called “break-even distance”) is over 600 km for overhead lines (OHLs) and 50~100 km for cables due to its lower power losses and capital cost compared with HVAC transmission [2].

Thyristor based line commutated converters (LCCs) have been employed in HVDC transmission since the 1970s. Due to the extensive research, field tests and operation in the past decades, the LCC-HVDC has become a highly-mature technology [3]–[4]. For example, the DC voltage and capacity of the Changji-Guquan ultra HVDC (UHVDC) link built by the China State Grid has reached to ± 1100 kV

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and 12 GW. The length of its transmission line is 3293 km [5]. However, the LCC-HVDC technology still has a few inherent shortcomings. For instance, the commutation failure, a large converter station footprint and DC voltage polarity reversal during power flow reversal [3], [6].

The voltage source converter based HVDC technology, especially the modular multilevel converter (MMC) based HVDC, has been developed to be an attractive alternative for its LCC counterpart thanks to its excellent features: no commutation failure, compact and scalable system design and weak AC grid operating capability [7]–[9]. The voltage and capacity ratings of MMC-HVDC have reached the UHVDC level. For example, the MMCs deployed in the Kun-Liu-Long project have reached to ± 800 kV with a capacity of 5 GW [6]. This provides technical feasibility to combine the two types of HVDC technologies to achieve hybrid LCC/MMC based HVDC and UHVDC systems [10].

The hybrid LCC/MMC system utilizes the merits of the two technologies. For instance, the Skagerrak hybrid LCC/MMC HVDC project, wherein the LCC and MMC links operate as the positive and negative poles to form a bipolar configuration [11]. In this architecture, the MMCs can alleviate commutation failures on the nearby LCC through fast reactive power support [12]. Moreover, compared with pure MMC-HVDC, the hybrid topology employs LCC as the rectifier and MMC as the inverter can not only reduce the capital cost and power losses but also avoid commutation failures. However, this topology is not suitable for offshore wind integration as the LCC station is too large to be built on an offshore platform [13]. The topology that uses the MMC as an offshore rectifier and the LCC as an onshore inverter can be a cost-effective solution for offshore wind power applications [14]. Although the problem of commutation failure still exists in this topology, the risk of commutation failures can be reduced by devising appropriate control strategies [15]–[17].

Commutation failure will lead to a short-circuit in the DC terminal of the LCC that operates as the inverter. Although the DC short-circuit is not destructive for LCC-HVDC systems due to thyristors' excellent capability to withstand large surge currents [18], it may result in severe overcurrent in insulated-gate bipolar transistor (IGBT) based MMCs in a hybrid LCC/MMC system. Moreover, due to the difference in configurations between half-bridge (HB) and full-bridge (FB) MMCs, their control strategies for mitigating commutation failures should be designed differently.

Additional devices, such as static var compensator, static synchronous compensator and synchronous condenser, can be utilized to mitigate the risk of commutation failures [19]–[21]. Re-designing the LCCs by adding additional modules,

such as thyristor and IGBT based controllable capacitors, can also alleviate the problem of commutation failure [22]–[24]. However, those solutions involve additional devices and therefore increase the capital cost, power losses and system complexity. Instead, mitigating the commutation failure through proper control strategies can be a cost-effective alternative. Moreover, there are different MMC DC system frameworks: HB-MMC based DC grids with DC circuit breakers (DCCBs) and FB-MMC based DC grids. However, the behaviors of the commutation failure in hybrid LCC/MMC systems with different MMC DC frameworks are still under-researched.

In this paper, the characteristics of hybrid LCC/MMC systems suffering commutation failure are analyzed. Both HB- and FB-MMCs have been studied with the consideration of different control strategies. Solutions for protecting multi-terminal hybrid LCC/(HB- and FB-)MMC networks have been investigated. The analysis has been verified through simulations conducted in PSCAD/EMTDC. The studies in this paper can provide technical guidance for mitigating commutation failures in future hybrid LCC/MMC HVDC systems.

2 Commutation failure

2.1 Mechanism

To ensure that the thyristors can regain the forward blocking capability, a safe extinction angle (turnoff time) is needed when the commutation overlap is completed. If the commutation overlap is longer than a normal condition or does not complete before the next forward voltage, the commutation may fail — the so-called commutation failure. In this case, the valve on the opposite pole in the same phase will be triggered in the next interval of $2\pi/3$ and therefore, lead to a short-circuit in the DC terminal of the converter [18], [25].

Fig. 1 shows an LCC operates as an inverter. During normal operation, the six valves commutate from T_1 to T_6 with an interval of $\pi/3$. The commutation from T_3 to T_4 is taken as an example to illustrate the process of a commutation failure.

If the commutation overlap between T_1 and T_3 is largely prolonged, for instance, by an AC side voltage drop, T_1 may continue to conduct when its voltage turns from negative to positive without a triggering signal. Meanwhile, no DC current flows through T_3 . T_4 will be triggered at the next triggering instant and then, the DC current will start to flow through T_1 and T_4 . This process is called commutation failure. The DC terminal is shorted, which further increases the DC current and aggravates the consequences. Fig. 1 illustrates the DC current path after the commutation failure.

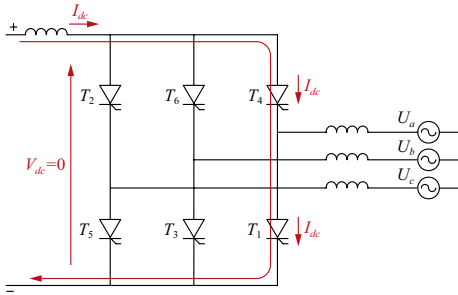


Fig. 1 DC current path in case of commutation failure

It can be seen from Fig. 1 that the DC current only flows through T_1 and T_4 . In this case, there is no voltage drop and fault current on the AC grid. It means the commutation failure does not result in a direct disturbance in the AC grid. The DC reactor limits the drop of DC voltage and the increase of current. The system may recover soon (several cycles) if the AC side voltage recovers.

In LCC-HVDC systems, α is the firing angle, β is the advanced firing angle, γ is the extinction angle and μ is the commutation overlap angle. The relationships of them are

$$\gamma = \beta - \mu = 180^\circ - \alpha - \mu \quad (1)$$

The commutation overlap angle μ is given by

$$\mu = \arccos \left(\cos \gamma - \frac{2X_C I_{dc}}{\sqrt{2}U_i} \right) - \gamma \quad (2)$$

where X_C is the equivalent commutation reactance and U_i is the rectifier's AC side voltage.

The DC current is

$$I_{dc} = \frac{V_{dcr} - V_{dci}}{R_l} \quad (3)$$

where R_l is the resistance of the transmission line and V_{dcr} and V_{dci} are the DC terminal voltages of the rectifier and inverter.

The DC terminal voltage of the inverter is:

$$V_{dci} = \frac{3\sqrt{2}}{\pi} U_i \cos \beta + \frac{3}{\pi} X_C I_{dc} \quad (4)$$

Equations (2)-(4) show that a voltage (U_i) drop in the AC grid will lead to a drop in the DC terminal voltage (V_{dci}). In this case, the increasing DC current will enlarge the commutation overlap angle and therefore, reduce the extinction angle, leading to a commutation failure. A reduction in the DC voltage and DC current during a commutation failure will decrease the commutation overlap angle and then enlarge the extinction angle. Therefore, a DC voltage control that regulates the DC voltage to a low value can be proposed to alleviate the commutation failure [15].

2.2 Commutation failure in hybrid LCC/MMC HVDC systems

System behaviors will be different in LCC-HVDC and

hybrid LCC/MMC HVDC systems. Fig. 2 shows the DC current paths during an inverter commutation failure in the LCC and hybrid LCC/MMC links. For simplicity, a 6-pulse LCC is used to represent a 12-pulse LCC. The R_l , L_l and C_l are the lumped equivalent resistance, inductance and capacitance of the DC transmission line.

It can be seen from Fig. 2(a) that a DC short-circuit will be created once a commutation failure occurs. The DC voltage will collapse immediately. The energy stored in the DC circuit will immediately discharge through the current paths, as shown in Fig. 2(a). According to the analysis in the previous subsection, the voltage drop will help alleviate the commutation failure. The C_l in an OHL based system will be smaller than in a cable based system [26]. A larger capacitance will provide a stiffer hold-up time of the DC voltage, which means the consequences of a commutation failure in a cable based system may be worse than in an OHL based system.

Unlike LCCs, there are DC capacitors in the submodules (SMs) in MMCs, as shown in Fig. 2(b). SM capacitors will discharge once there is a DC short-circuit. The equivalent capacitor of an MMC is much larger than that of the transmission line. Therefore, compared with the LCC based system, hybrid LCC/MMC systems experience a more gradual reduction in DC voltage. As a result, the consequences of commutation failure in the hybrid LCC/MMC system may be worse than in the pure LCC-HVDC system.

As IGBTs cannot compete with thyristors in terms of overcurrent capability, MMCs will be blocked once a large fault current is detected. Moreover, the topologies of blocked HB- and FB-MMCs are different. This implies that fault behaviors of the HB- and FB-MMCs based hybrid LCC/MMC systems are also different.

Taking the LCC/HB-MMC system as an example, the MMC becomes an uncontrollable bridge once it is blocked. Fig. 2(c) shows the equivalent circuit after blocking the HB-MMC. The figure reveals that the SM capacitors stop discharging due to the forward-bias characteristic of diodes. However, AC currents will feed into the DC side through the diode bridge. The AC infeeding currents contribute to the DC current in the inverter. This will not only exacerbate the commutation failure but also lead to high AC and DC fault currents and affect the rectifier's AC side voltage.

Before blocking the FB-MMC, the fault behaviors of the HB- and FB-MMC based hybrid LCC/MMC systems are the same. However, fault behaviors will be different once the FB-MMC is blocked. Fig. 2(d) shows the equivalent circuit after the FB-MMC is blocked. Due to the configuration of the blocked FB-SM, the capacitors will not

be able to discharge [27]. Moreover, as the capacitor DC voltage is higher than the valve-side AC line-to-line voltage, there will be no AC side infeeding currents. In this case, the DC current will immediately drop, which will help mitigate the commutation failure. Because there is no current path in the blocked FB-MMC, the energy stored in the DC reactor (L_{dc}) will be dissipated by the distributed parameters of the DC circuit. This discharging process depends on the circuit parameters and may take a while. It should be noted that the FB-MMC may regulate the DC voltage to near zero with its flexible DC voltage control capability instead of blocking itself [28], which will be analyzed in the following sections.

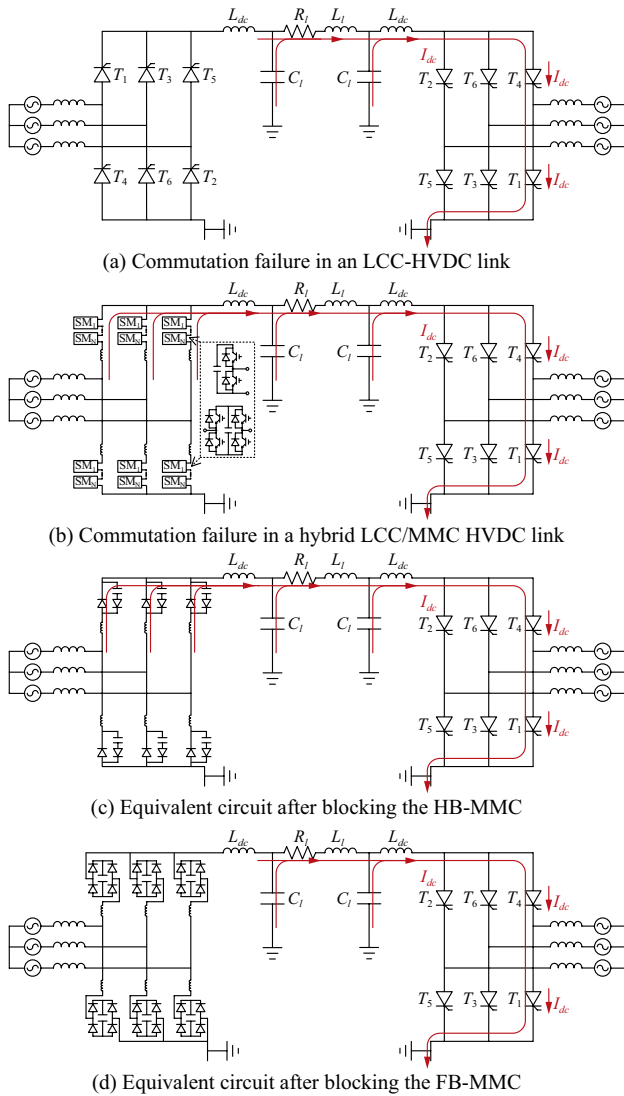


Fig. 2 DC current paths during a commutation failure

2.3 Control strategies for mitigating commutation failures in hybrid LCC/MMC HVDC links

The analysis in the previous subsection shows that the consequences of a commutation failure in a hybrid LCC/

MMC system may be worse than in an LCC system due to the internal capacitors of MMCs. In addition, the fault behaviors of an HB-MMC based hybrid system will be worse than in an FB-MMC based hybrid system, because of the free-wheeling diode bridge of the blocked HB-MMCs. In order to reduce the probability of commutation failures and improve the system recovery process, appropriate control strategies need to be designed with the consideration of HB- and FB-MMCs' intrinsic characteristics.

The voltage dependent current order limiter (VDCOL) is commonly applied in the DC current control at the inverter side of an LCC-HVDC system to change the current setting, if a low voltage is detected. Fig. 3 shows the characteristics of the VDCOL used in the CIGRE First Benchmark model [29].

The VDCOL helps reduce the DC current during DC short-circuit and therefore, helps reduce the occurrence of a commutation failure.

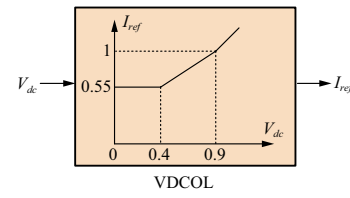


Fig. 3 Relationship between the LCC's DC current reference and the DC voltage

The analysis in Section 2.1 shows that reducing the DC voltage during a commutation failure can be an optional solution for reducing the probability of commutation failures. A voltage dependent voltage order limiter (VDVOL) has been proposed in [15] to enhance the resistance of hybrid LCC/HB-MMC HVDC systems against commutation failures. The DC voltage of the MMC is adjusted depending on the AC voltage of the LCC. The DC voltage reference is generated according to the pre-set relationship of LCC's AC side voltage and the DC voltage reference, as shown in Fig. 4.

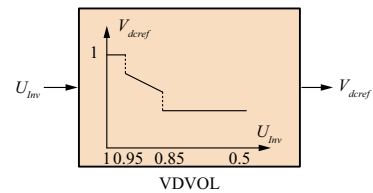


Fig. 4 Relationship between LCC's AC voltage and HB-MMC's DC voltage reference

It can be seen from Fig. 4 that the DC voltage reference V_{dcref} will be reduced if there is a drop in the LCC's AC side voltage U_{inv} . It should be noted that V_{dcref} cannot be reduced

below a certain threshold due to the limitation of the HB-MMC which needs a high DC voltage to ensure stable operation. Therefore, this control strategy can only enhance the resistance against commutation failure but cannot eliminate it. Moreover, fast communication is needed to transmit the voltage control signal from LCC to MCC.

Thanks to its configuration, FB-MMC can regulate the DC voltage from 1 to -1 p.u. [28]. This means that the DC voltage margin for FB-MMCs is much larger than HB-MMCs. Therefore, the FB-MMC can be controlled to work in a low voltage mode during a commutation failure. Additionally, as the FB-MMC is still operating during the low voltage operation, it can keep regulating its AC side voltage or frequency. Thus, the negative impact on its AC side can be mitigated.

It should be emphasized that the VDCOL of LCC will work automatically to reduce the DC current reference based on its local measurement of the DC voltage, while the action of the VDVOL of the MMC needs the communication system [15].

2.4 Protection strategies in multi-terminal hybrid LCC/MMC HVDC networks

The above DC voltage control strategies can be applied in point-to-point HVDC links. However, they may not be applicable to multi-terminal hybrid LCC/MMC HVDC networks. The reason is that the reduction in DC voltage affects the entire DC network and therefore, affect the stable operation of other stations.

Fig. 5 shows a hybrid LCC/MMC multi-terminal DC (MTDC) grid wherein the two MMCs operate as rectifiers and the two LCCs operate as inverters. Such a hybrid MTDC network can be a cost-effective solution for large-scale offshore power wind transmission systems, in which the MMCs operate as offshore stations and the LCCs operate as onshore stations.

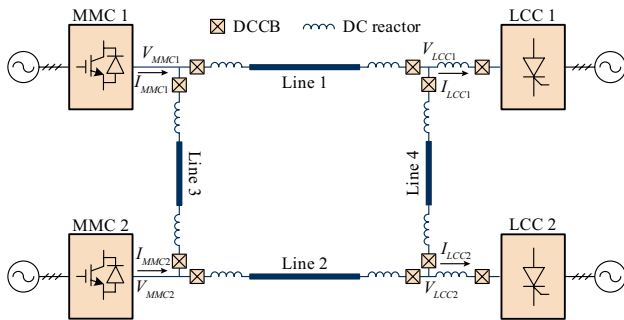


Fig. 5 Hybrid LCC/MMC DC grid with DCCBs

DCCBs can be deployed at the two ends of each DC line to protect the system by isolating the faulted zones

from the healthy areas. Moreover, DCCBs can be deployed at the terminal of each LCC to isolate the LCC suffering commutation failure. This DCCB can also serve as a backup protection if the DCCBs in the transmission line experience failures.

As commutation failure creates a short-circuit in the DC terminal of an LCC, DCCBs are able to interrupt the DC overcurrent and isolate the LCC suffering from commutation failure from the DC circuit. Then, the LCC can be reconnected to the DC network once its AC fault is cleared.

3 Case studies and analysis

To verify the analysis in the previous sections, LCC-HVDC and hybrid LCC/MMC HVDC systems have been investigated through simulations conducted in PSCAD/EMTDC. The index of fault level (FL) defined in [15] is used to describe the severity of commutation failure caused by an AC fault. Equation (5) defines FL :

$$FL = \frac{U^2}{ZP} \times 100\% \quad (5)$$

where U is the voltage of the AC grid, Z is the fault impedance and P is the rated active power of the converter. It can be seen from the equation that the smaller the fault impedance, the more severe the failure. A critical FL (FL_{cri}) is defined as the minimum FL that leads to a commutation failure.

It should be mentioned that the work of this paper focuses on the system level control and protection strategies of hybrid LCC/MMC HVDC systems. The studies would be applicable for different AC system strength (short-circuit ratio, SCR) of the LCC. Herein, the tests are conducted in a typical weak grid condition. LCCs would be more resistant to commutation failures in case of a higher SCR. Therefore, an SCR = 2.5 has been considered in this work.

3.1 LCC and hybrid LCC/MMC HVDC links

To compare the differences in the system dynamic responses caused by commutation failures in pure LCC and hybrid LCC/MMC systems, two types of HVDC links shown in Figs. 2(a) and (b) have been built in PSCAD. System parameters of the two systems are shown in Table 1.

Data of the frequency dependent OHL model is taken from [30] and given in the Appendix. The length of the OHL is 600 km. The LCC models and their AC grids are taken from the CIGRE First Benchmark model [29]. As the number of SMs does not affect the equivalent circuit of a converter once it is blocked, a detailed switching model with 10 SMs in each arm has been implemented to ensure

acceptable simulation times. Control systems of the LCC and MMC are shown in Fig. 6.

In the hybrid LCC/MMC links, both HB- and FB-MMCs have been modeled. The MMC controls the reactive power (Q) and the DC voltage. The LCC controls the DC current with the VDCOL. If an AC fault is detected at the LCC, the VDVOL will regulate the DC voltage to 0.7 p.u. of the HB-MMC and 0.1 p.u. of the FB-MMC.

Table 1 System parameters

MMC Parameters	Values
Capacity (MVA)	1000
Rated DC voltage (kV)	500
Rated AC voltages (kV)	230
Transformer capacity (MVA)	1250
Transformer ratio (kV/kV)	230/245
Transformer leakage inductance (p.u.)	0.18
DC terminal reactance (H)	0.1
Number of SMs in each arm	10
SM capacitance (mF)	2.5
Arm inductance L (H)	0.025
Arm resistance R (Ω)	0.1
AC system SCR	3
LCC Parameters	Values
Capacity (MVA)	1000
Rated DC voltage (kV)	500
Rated AC voltages (kV)	230
Transformer capacity (each valve) (MVA)	592
Transformer ratio (kV/kV)	230/209
Transformer leakage inductance (p.u.)	0.18
DC terminal reactance (H)	0.5968
AC system SCR	2.5

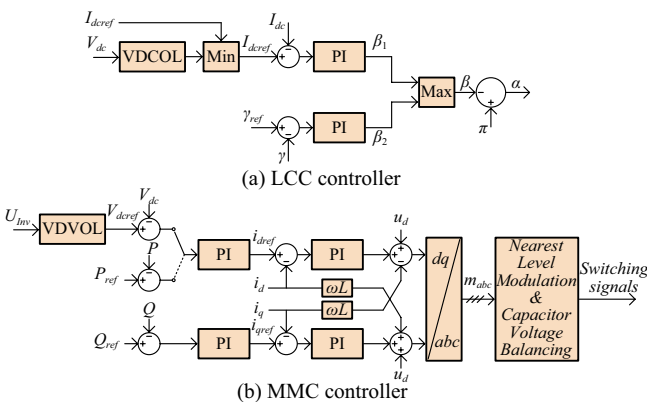


Fig. 6 LCC and MMC control systems

Fig. 7 shows the dynamic responses of the LCC-HVDC link. A single-phase-to-ground (SPG) fault with a resistance of 117Ω has been set at $t = 2$ s in phase A at the inverter's grid-side AC bus. The fault lasts 0.2 s. In this case, $FL_{cri} = 45.21\%$. It can be seen that LCC's DC voltage collapses and the DC current increases immediately when the AC fault leads to commutation failures. The DC fault current reaches to 2.01 p.u. During the commutation failure, the power transmitted to the AC grid has been affected and the AC voltage is disturbed. It should be noted that the system suffers continuous commutation failures within the interval of the AC fault. The system recovers to normal operation when the AC fault is cleared.

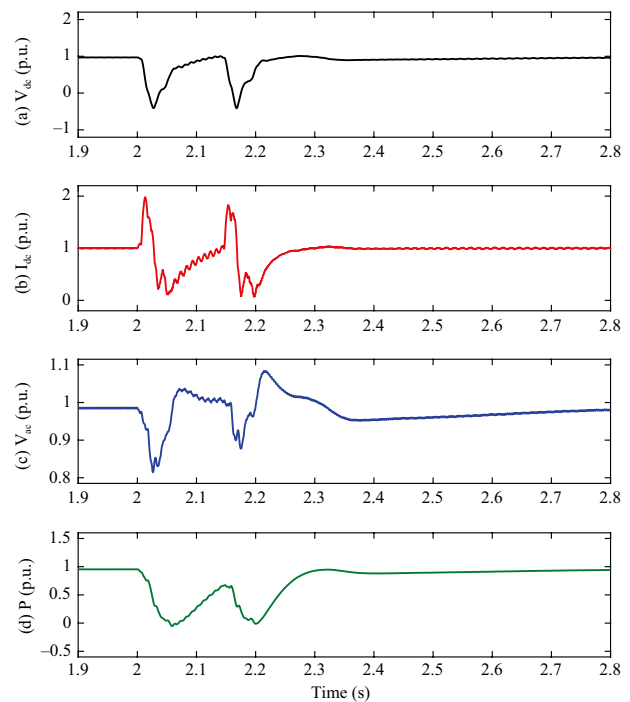


Fig. 7 System responses in LCC-HVDC link

Fig. 8 illustrates the dynamic responses of the hybrid LCC/HB-MMC HVDC link. In this case, the AC fault resistance is 169Ω and FL_{cri} is 31.30%. This means that the FL is lower than in the last case. However, the commutation failure still occurs even for less severe fault. The HB-MMC is blocked based on its local protection: either any arm current exceeds 3 kA and/or the DC terminal voltage is lower than 0.8 p.u. or higher than 1.2 p.u. of the rated DC voltage. As the DC fault keeps feeding into the inverter through the uncontrollable bridge, the commutation failure still exists and the fault current reaches 4.10 p.u. The AC voltage drops and the power transmission is totally interrupted during the commutation failure. As large AC currents keep feeding into the DC circuit, the system will

continue to experience commutation failure, unless the current path is interrupted by tripping MMC's AC circuit breaker (ACCB).

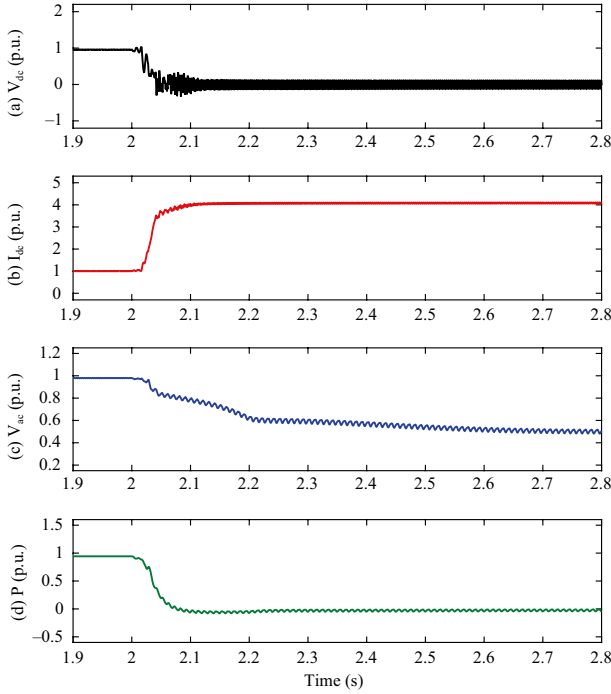


Fig. 8 System responses in hybrid LCC/HB-MMC HVDC link

Fig. 9 shows the dynamic responses of the hybrid LCC/HB-MMC HVDC link, where the VDVOL has been applied in the HB-MMC. To investigate the effectiveness of the VDCOL, a more severe fault with a resistance of 88Ω and an $FL = 60.11\%$ has been set. A 3 ms delay is used to simulate the commutation delay for transmitting the low voltage signal from the LCC to the MMC. It can be seen from Fig. 9 that the VDVOL reduces the DC voltage to 0.7 p.u. during the AC fault. Double-frequency oscillation appears in the DC voltage due to the unbalanced AC fault. Moreover, the VDCOL shown in Fig. 3 has been applied in the inverter and works automatically to reduce the DC current reference when the DC voltage is reduced. As a result, there is no commutation failure. The DC voltage is ramped up to 1 p.u. with a slope of 0.1 s when the AC fault has been cleared. The active power has been reduced but not entirely interrupted. The system recovers to normal operation when the fault has been cleared, and the voltage ramps up to the rated value gradually.

Fig. 10 depicts the dynamic responses of the hybrid LCC/FB-MMC HVDC link, where the VDVOL is applied in the FB-MMC. A much more severe SPG fault with a resistance of 8Ω and an $FL = 661.25\%$ has been set. The results reveal that the DC voltage is regulated to 0.1 p.u. by

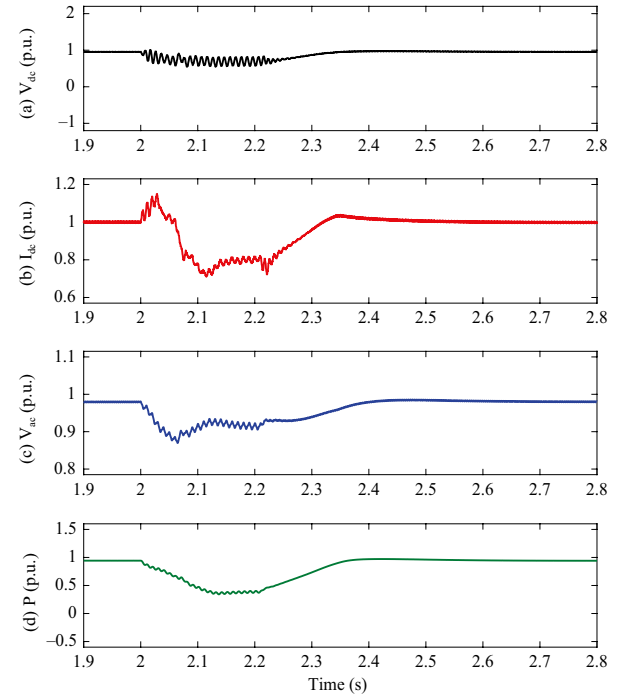


Fig. 9 System responses in hybrid LCC/HB-MMC HVDC link with the VDVOL in HB-MMC

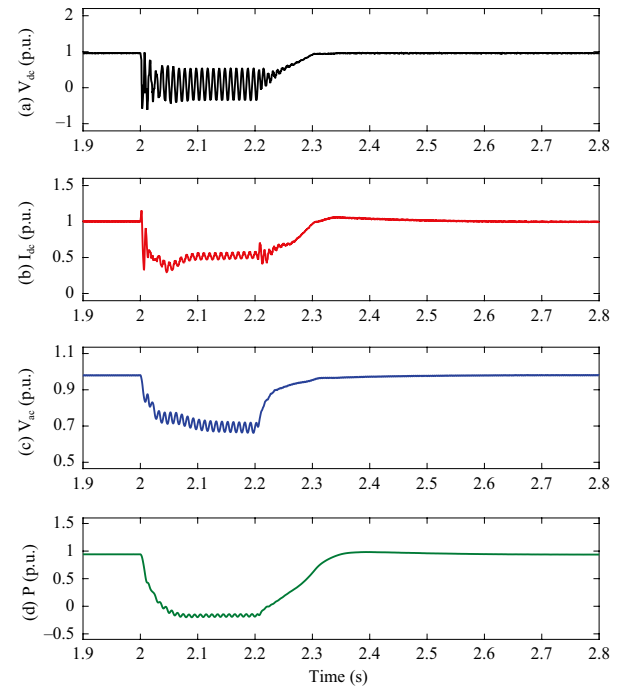


Fig. 10 System responses in hybrid LCC/FB-MMC HVDC link with VDVOL in FB-MMC (SPG fault)

the FB-MMC's VDVOL, and the DC current is reduced to 0.55 p.u. by the LCC's VDCOL. No commutation failure occurs. The large double-frequency oscillation of the DC voltage is caused by the severe unbalanced AC fault. Therefore, the oscillation is more serious in the first tens milliseconds.

Because the AC fault is much more severe than the last case, the magnitude of the double-frequency oscillation in Fig. 10 (a) is larger than that in Fig. 9(a). In addition, due to the severe AC fault, the AC voltage drop is worse, and the power transmission has been interrupted. The system starts to recover, and the DC voltage is controlled to the rated value when the AC fault has been cleared. It should be mentioned that the system can still transmit partial power if the DC voltage is regulated to a higher level. The study demonstrates the control capability in the worst scenario only.

To investigate the effectiveness of the FB-MMC's capability in mitigating commutation failure, a more severe three-phase-to-ground fault with a fault resistance of 8Ω has been tested. Fig. 11 shows the dynamic responses of the system. The DC voltage is regulated to 0.1 p.u. when the AC fault has been detected. Similar to the previous case, the oscillation of the DC voltage is caused by the large DC reactor of the LCC. The DC current is regulated to 0.55 p.u. by the LCC's VDCOL. The system operates in the low DC voltage mode during the AC fault. Commutation failure has not occurred. The system restores quickly when the AC fault has been cleared.

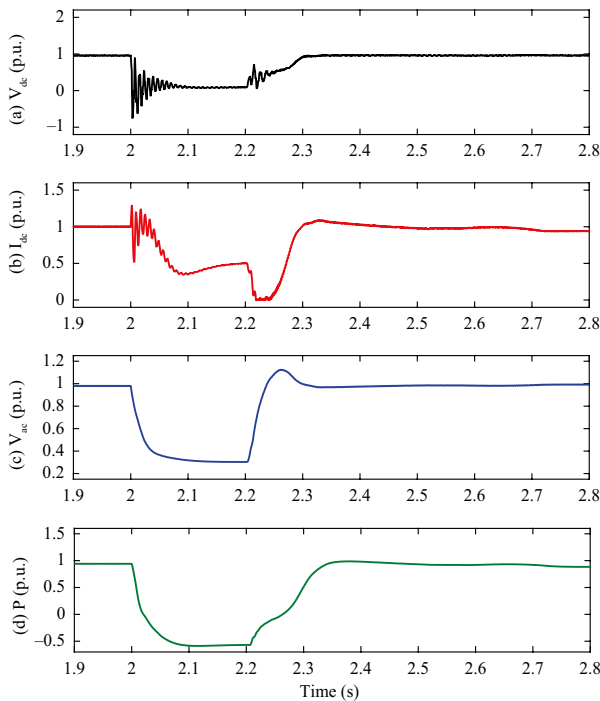


Fig. 11 System responses in hybrid LCC/FB-MMC HVDC link with VDVOL in FB-MMC (three-phase AC fault)

3.2 Multi-terminal hybrid LCC/MMC HVDC networks

To investigate system behaviors and protection strategies of commutation failure in multi-terminal hybrid LCC/

MMC HVDC networks, the system shown in Fig. 5 has been built in PSCAD. HB-MMCs are used in the system. The parameters of the converters and OHL are the same as in the previous case. The lengths of the lines 1&2 are 550 km and 150 km for lines 3&4. The two MMCs operate as rectifiers and the two LCCs operate as inverters. MMC1 controls the reactive power and DC voltage and MMC2 controls the active and reactive power. The LCCs 1 and 2 control DC currents. An SPG fault with a resistance of 8Ω ($FL = 661.25\%$) is set at the AC bus of LCC1 at $t = 2$ s. The fault lasts 0.2 s. The MMCs are blocked based on the same criteria as in the last section. The measurements of the terminal voltages and currents are illustrated in Fig. 5.

A. AC circuit breaker based protection strategy

ACCB is equipped in the grid-side of each converter, which can be an economical solution for DC grid protection. In this section, ACCB based protection is studied.

Fig. 12 shows the dynamic responses of the system. The AC fault at LCC1 results in a commutation failure that creates a short-circuit in the DC terminal of LCC1, as shown in Fig. 12(c). Then, DC currents start to increase and DC voltages start to collapse. The overcurrent has led to the blocking of the HB-MMCs, as shown in Figs. 12(a) and (b). Then, large fault currents feed into the DC circuit through MMCs' uncontrollable diode bridges. The fault currents keep increasing and feeding into the short-circuit generated by the commutation failure.

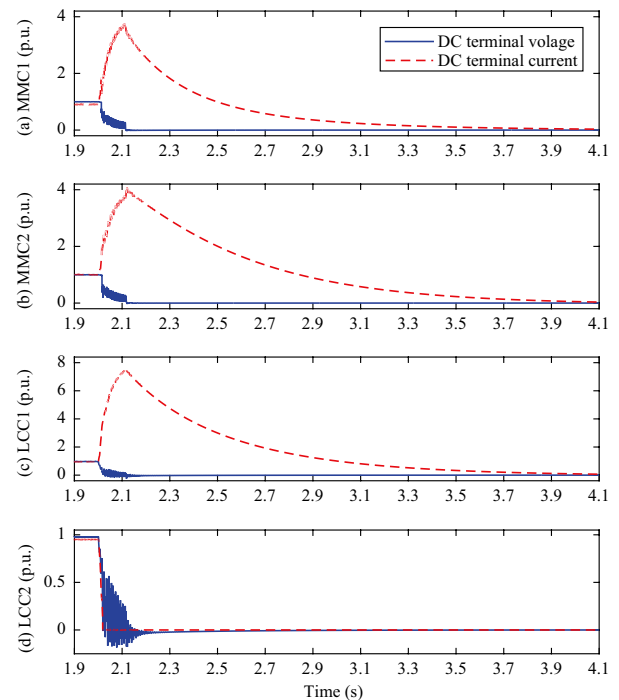


Fig. 12 System responses of ACCB based protection

As analyzed in the previous section, the short-circuit will never disappear until the tripping of MMCs' ACCBs. Therefore, the LCCs have been blocked 20 ms after the occurrence of commutation failure. This is the reason why there is no overcurrent or commutation failure of the LCC2, as shown in Fig. 12(d). MMCs' ACCBs have been tripped following their blocking. A period of 100 ms is applied to simulate the opening time of the ACCBs. The DC currents start to decline immediately once the ACCBs are tripped. The current paths of the residual current are illustrated in Fig. 13. As shown in Fig. 12, the residual currents take more than 2 s to decay to zero.

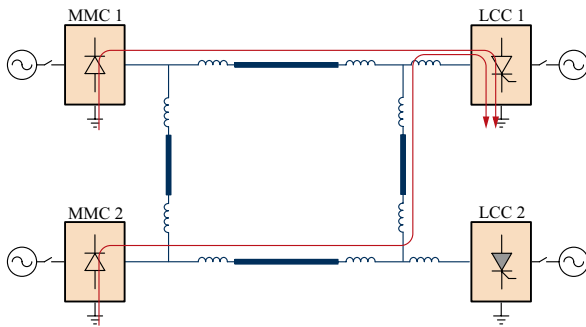


Fig. 13 Current paths of the residual fault currents

B. DC circuit breaker based protection strategy

It can be seen from the above analysis that the ACCB based protection will lead to the outage of the entire DC network. Moreover, due to the long decay time of the residual DC currents, the diodes and thyristors in the blocked MMCs and LCCs may experience severe overtemperature and even get damaged. To shorten the protection time and reduce the negative impact on the operation of the DC network, the DCCB based protection may be a solution. In this study, the simplified DCCB model used in [31] has been deployed in the PSCAD model, as shown in Fig. 14. A period of 5 ms is used to simulate the opening time.

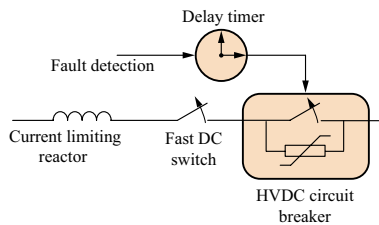


Fig. 14 Simplified DCCB

Fig. 15 shows the dynamic responses of the system using the DCCB based protection strategy. The DCCB in the terminal of LCC1 has been tripped upon detecting a commutation failure. A 2 ms delay is used to simulate

the fault discrimination time. Due to the large smoothing reactor of the LCC, the DC voltage experiences severe oscillations, as shown in Fig. 15(c). As the distance between LCC1 and LCC2 is short, the DC voltage oscillations will cause a commutation failure at LCC2, which will, in turn, lead to cascading commutation failures. Therefore, the LCC2's DC terminal DCCB is tripped following the tripping of LCC1's DCCB. As the two inverters have been tripped, the change of the power flow may lead to serious overcurrent and voltage oscillations. Therefore, MMC2's power is immediately reduced to zero. A period of 5 ms is used to simulate the delay of the communication system. It can be seen from Fig. 15 that the MMCs are not blocked and the system reaches a stable condition after the transient processes.

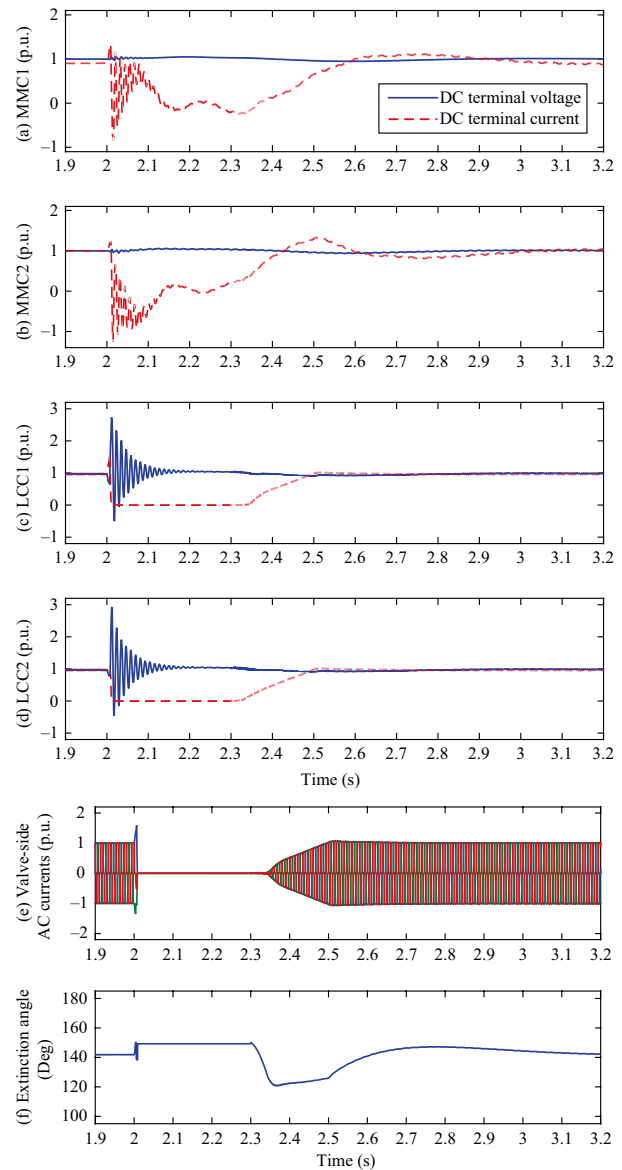


Fig. 15 System responses of DCCB based protection

The restoration of the system follows the control strategy proposed in [10]. First, the DCCBs are closed at zero current. The LCCs were deblocked and the power is ramped up with a slope. To balance the power flow, the MMC2 follows the LCCs' power ramp-up. Figs. 15(e) and (f) show the valve-side currents and extinction angle of the low-voltage valve bridge of LCC1.

Although the DCCB based protection also leads to an interruption of the DC network, it can quickly isolate the LCCs suffering commutation failures. However, the DCCB based method does not lead to the de-energization of the whole DC network. Therefore, the outage time is much shorter than the ACCB based method and the post-fault restoration process is much easier.

It can be seen that the DC voltage and current in the DC circuit experience severe oscillations during the initial transient period. The reason behind this phenomenon is that the operation of the DCCBs interrupts the current paths of the LCCs, which induces the severe transient period. Moreover, the energy stored in the large smoothing reactors of LCCs and the current limiting reactors will discharge through the distributed parameters of the DC circuit. Therefore, the interactions between current limiting reactors and the DC transmission lines result in the oscillations. In reality, the overvoltage during the oscillations must be limited by surge arresters deployed in the terminals of DC transmission lines [26].

4 Conclusions

Hybrid LCC/MMC HVDC systems combine the merits of both LCC and MMC. However, the system still will experience commutation failures if an LCC operates as an inverter. This paper investigated the commutation failure in hybrid LCC/MMC HVDC systems with the consideration of different types of MMCs and control and protection strategies.

The studies demonstrate that a hybrid LCC/MMC HVDC may be more vulnerable to a commutation failure compared with a pure LCC HVDC due to the DC capacitor of MMCs. Moreover, the DC voltage control of HB-MMC can reduce the possibility of commutation failures but cannot eliminate it. Thanks to its flexible DC voltage control capability, the FB-MMC can largely reduce the probability of commutation failure by regulating its DC voltage to a very low value. The FB-MMC based system can also mitigate the negative impact on FB-MMC's AC grid and achieves a fast system restoration. However, the high costs and power losses of FB-MMCs may limit their applications.

Although the ACCB based protection for multi-terminal

hybrid LCC/MMC HVDC networks is an economical solution, it will lead to a long-time system outage. The DCCB based protection can quickly isolate the LCCs suffering from a commutation failure. However, the deployment of DCCBs will increase the capital cost, which may limit their applications.

The findings of this paper may contribute to the design of control and protection strategies for hybrid LCC/MMC HVDC systems. Optimal protection strategies should be designed properly to achieve fast protection and mitigate the negative impacts on the system's stability.

Appendix A

The dimensions and parameters of the OHL used in this paper are shown in Fig. A1.

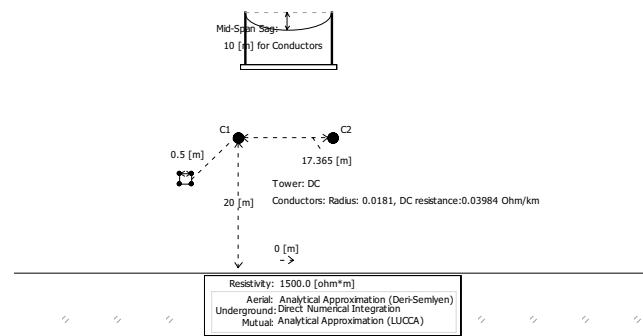


Fig. A1 Dimensions and parameters of the OHL

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